Integrated Sensing and Decision Support

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With the advent of modern electronics, the development of advanced sensing technologies has led to an explosion in the amount of data available to decision makers in many fields. Unfortunately, despite optimism to the contrary, the ability of humans to understand and respond to this growing flood of information has not kept pace. Lincoln Laboratory has launched a multidisciplinary research initiative in integrated sensing and decision support (ISDS) with the goal of improving decision performance across a variety of military and civil applications by augmenting advanced sensors with novel information exploitation and management techniques.

The history of remote sensing is intimately entangled with supporting military decision making through the processes of intelligence, surveillance, and reconnaissance (ISR). While the principles of military intelligence are ancient [1, 2], the application of sensing technology to reconnaissance did not begin until the development of photographic and electronic surveillance techniques during World Wars I and II [3]. Since then, the U.S. Department of Defense has made significant and ongoing investments in the development of sensing capabilities for military applications [4]. Today, many of those capabilities have found equally compelling applications in the civil sector—from the use of long-range radar for air traffic control to the development of earth-observing satellites for environmental monitoring and research.

As remote-sensing technology has advanced, the amount of data available to decision makers has increased at an ever-accelerating rate. While gathering surveillance and reconnaissance data has long been recognized as the key enabler for lifting the "fog of war," the ability to manage and exploit large volumes of data from multiple sources has emerged as the central challenge for supporting decisions. This challenge encompasses nearly all data-centric decision domains, including geopolitics, law enforcement, medical diagnostics, finance, regulatory affairs, consumer choice, and even recreational pursuits such as gambling and other forms of game playing.

Human cognition is not well suited to accurately perceiving large amounts of information and possible courses of action—especially when that information is intrinsically statistical in nature [5, 6]. This limitation gives rise to the temptation to attempt complete automation of data-driven decision processes. While this approach can be appropriate for certain repetitive, low-risk applications, most decision problems demand some degree of human control to ensure adaptability to unanticipated circumstances.

The integrated sensing and decision support (ISDS) initiative at Lincoln Laboratory seeks to identify, characterize, and develop automated information management and exploitation technologies to augment the unique cognitive capabilities of human decision makers. The ISDS initiative operates as an ensemble of parallel research and development programs across a variety of application domains including air and missile defense, space surveillance, Navy strike and special operations, and air traffic control (including weather sensing and collision avoidance). One of the most significant challenges in the ISDS initiative has been identifying a common framework in which to understand the decision support challenges unique to each of these sensor-centric applications. Due to the central role of the deci-

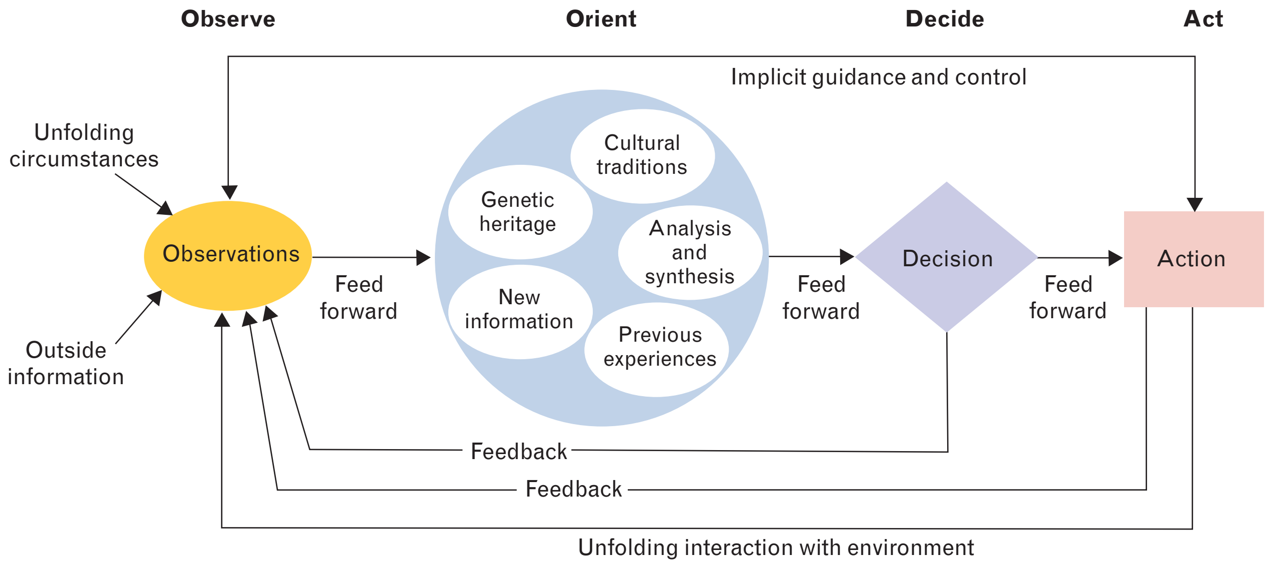

FIGURE 1. The observe-orient-decide-act (OODA) loop highlights the multitude of factors and interactions that shape decision makers' perception of unfamiliar or changing situations [7]. The OODA loop has been an influential construct for understanding decision making—especially in the military domain.

sion maker in each application, the unifying framework emerges as a model of the decision process itself.

Modeling the Decision Process

Large-scale human endeavors, such as military campaigns, involve a hierarchy of decision makers, from the foot soldiers on the front line through the intermediate force managers to the high-level theater commanders. Each increase in scope compounds the complexity of decision making as more situations need to be considered, more evidence needs to be weighed, and more options for action must be reviewed. The option to consider more situations, to gather more data, to perform more analyses, and to compare more alternatives for action render decision making more complex, without necessarily increasing the likelihood of successful outcomes. Although decision makers at all levels may share the same overall objective, their individual perspectives and experiences will independently influence their approach to the decision process—often with unexpected and potentially unfortunate consequences.

One of the best-known models for the human decision process, at least within the context of military applications, is the observe-orient-decide-act (OODA) loop developed by U.S. Air Force Colonel John Boyd [7]. The key elements of the OODA loop, illustrated in Figure 1, are the variety of information sources that contribute to situational understanding and the multiple tiers of feedback and feed-forward interactions. These elements emphasize the dynamic and oftentimes recursive nature of collecting and assessing information to support decision making. The doctrine of "maneuver warfare" [8] recognizes the importance of taking actions to deliberately disrupt the decision cycle of an adversary in order to control the tempo and, ultimately, the outcome of a conflict.

The OODA loop model leaves the details of the decision process itself vague in the recognition that decision making can be highly idiosyncratic. To lend more predictability to the process, many organizations have instituted formalized decision-making techniques. The U.S. Army, for example, has developed the Military Decision Making Process (MDMP) to provide a reliable method for constructing mission plans from received orders [9]. The MDMP, summarized in Figure 2, is centered around a systematic analysis of goals, an intelligence process to estimate the current state of the battlefield, the development of potential mission plans by the operations staff, and a war-gaming process that estimates the possible future states of the battlefield associated with each plan. The decision process is largely reduced to identifying the course of action that drives the battlefield closest to the mission goals.

While designed to explicitly coordinate the activities of multi-person battle staffs, the MDMP identifies a key feature of the decision process even as it occurs inside

the minds of individual decision makers—the selection of actions based on estimates of how those actions will change the state of the system under consideration. Usually, the system to be modified is the world in which we live. More specifically, the system is a particular subset of this world, such as a battlefield for military decisions, the collections of personal belongings that drive consumer decisions, or more fanciful constructs such as game boards or playing fields that provide contrived environments for recreational decision making. Clearly, the effectiveness of a decision process based on simulation of potential future states depends on developing an accurate model for the evolution of the system and priming that model with an accurate representation of the current system state. It has been postulated that augmenting the observe and orient functions of the OODA loop with the projection of likely future states describes the process by which humans develop and maintain awareness of complex situations in dynamic environments [10].

Examinations of decision making in a variety of settings reveal that, while estimation of future states is fundamental to selecting courses of action, the process of generating those estimates is often highly synopsized. In the recognition-primed decision model, outlined in Figure 3, both the recognition of situations and the selection of actions can, under familiar circumstances, be replaced with prototypes or analogs that are drawn from the decision maker's past experiences [11]. Only when faced with unfamiliar or anomalous information does the decision maker need to develop novel courses of action.

This synopsis of large elements of the decision process through pattern recognition is common in highly experienced individuals and is fundamental to making decisions in complex environments under significant time constraints or other types of pressure. As elements of the decision process are delegated to machine automation, exploiting situation and action prototypes facilitates the development of decision support systems that can most effectively utilize the unique cognitive capabilities of human decision makers to address unanticipated scenarios.

As part of the ISDS initiative, we have developed a simple decision model that captures key features of the work described in this overview. The ISDS decision model, illustrated in Figure 4, focuses on the processes internal to the decision maker required to support decisions to modify the environment; such modification is achieved through the employment of generic actuators on the basis of information derived from that environment from similarly generalized sensors. The core of the decision process is the simulation of potential future situations from an estimate of the current situation and an ensemble of courses of action hypothesized to meet the goals of the decision maker. Finally, situation and action templates are indicated as potential synopses of multiple elements of the decision process.

Although ISDS is the focus of a specific new initiative at Lincoln Laboratory, the problem being addressed is shared by all of the Laboratory's missions. Thus we can reasonably assume that the research described here will continue to identify and develop common technologies across mission domains, so that in the future sensor exploitation services developed for one mission will be able to accommodate the needs of other missions as well.

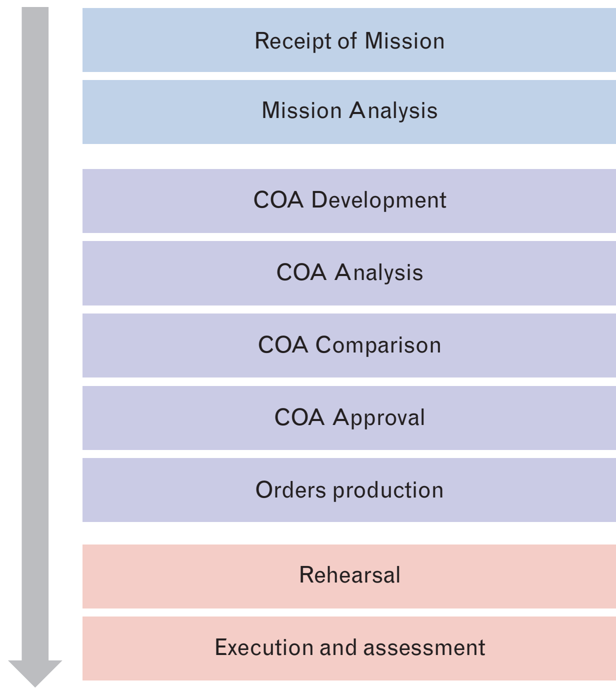

FIGURE 2. The U.S. Army's Military Decision Making Process (MDMP) emphasizes the development and analysis of courses of action (COA) as central to the decision process [9]. Intended to coordinate the actions of multiple staff officers, the MDMP defines a formal process that, in practice, can be streamlined as circumstances allow or require. Unlike the OODA loop, the MDMP does not describe an explicit observation function; instead, it focuses on the details of how decisions are formulated and approved.

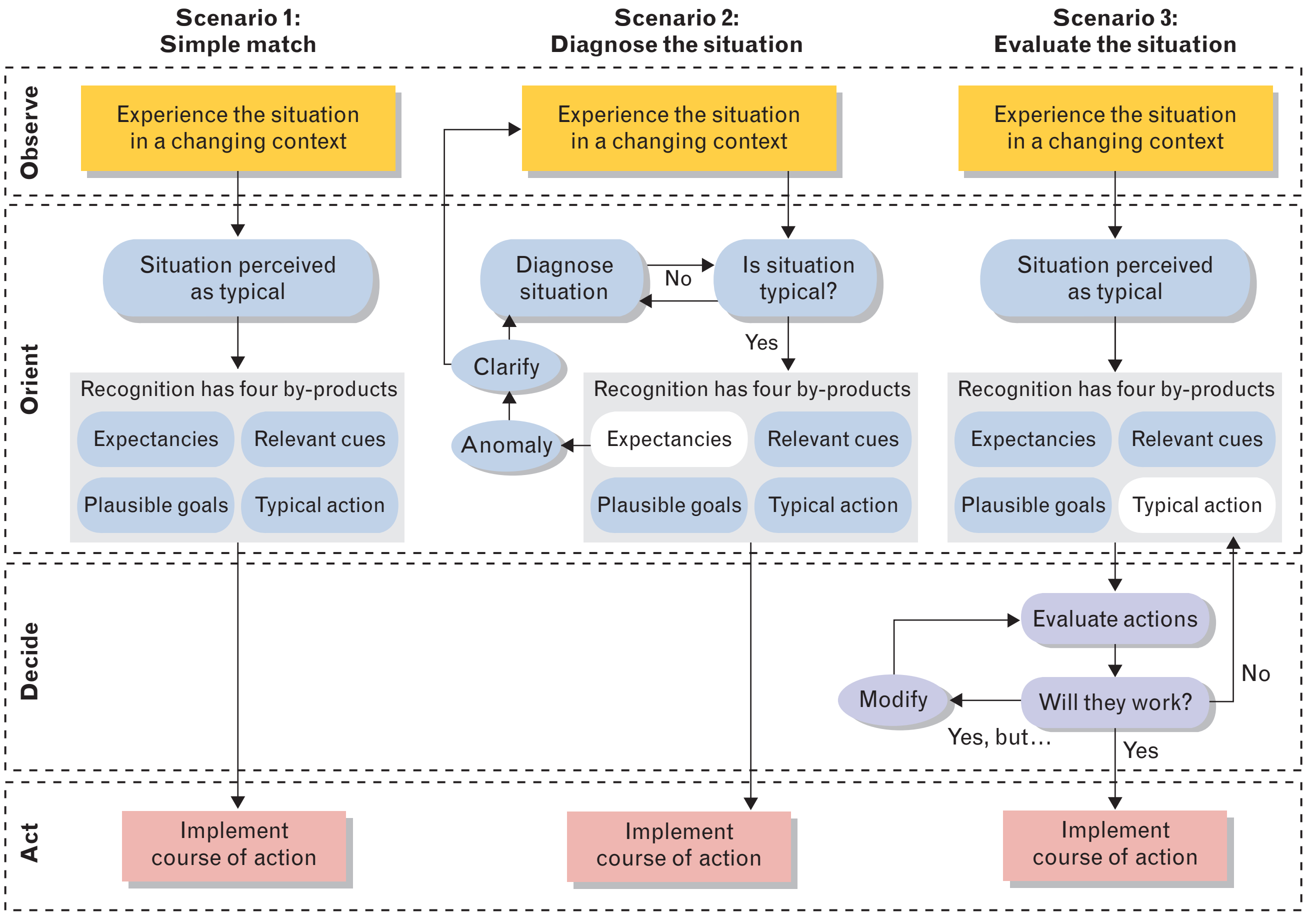

FIGURE 3. The Recognition-Primed Decision (RPD) model identifies three fundamental scenarios in which varying degrees of operator recognition can simplify large portions of the decision process [11]. In the first scenario, familiar situations can be matched with typical actions to facilitate rapid decisions resulting in well-known effects. In the second scenario, an unfamiliar situation forces the decision maker into a diagnostic process in order to develop the set of expectancies required to select a course of action from his repertoire. In the third scenario, a satisfactory action may not exist to address even a familiar situation. In this case, a mental simulation process may be required to develop and select an appropriate course of action. An unfamiliar situation requiring a novel course of action can be represented by a combination of the second and third scenario.

ISDS in Action

To illustrate work in support of the decision process framework, we have chosen seven examples from the civil and defense missions under study at Lincoln Laboratory. A recurring theme in these examples is the substantial increase in the use of automated techniques to supplement the manual decision support processes currently in use. Computer modeling and simulation are being developed to provide robust situation and action templates, as well as to supplement large-scale field exercises with artificially rendered data in support of operator training and the evaluation of decision architecture effectiveness. In addition, when the decision time horizon permits, physics-based, real-time computational models are being deployed to help the decision makers visualize the potential impact of courses of action.

Evaluating a Decision Support Architecture

Paula Pomianowski and colleagues discuss the instrumentation of a large, operationally relevant field exercise (Silent Hammer) with tools to relate the measures of performance of the deployed decision architecture to the overall measures of effectiveness of the field operation. Among the automation tools under test in this experiment was a self-synchronizing Metadata catalog that was used to manage the data flow between analysts and commanders over a limited-bandwidth communica-

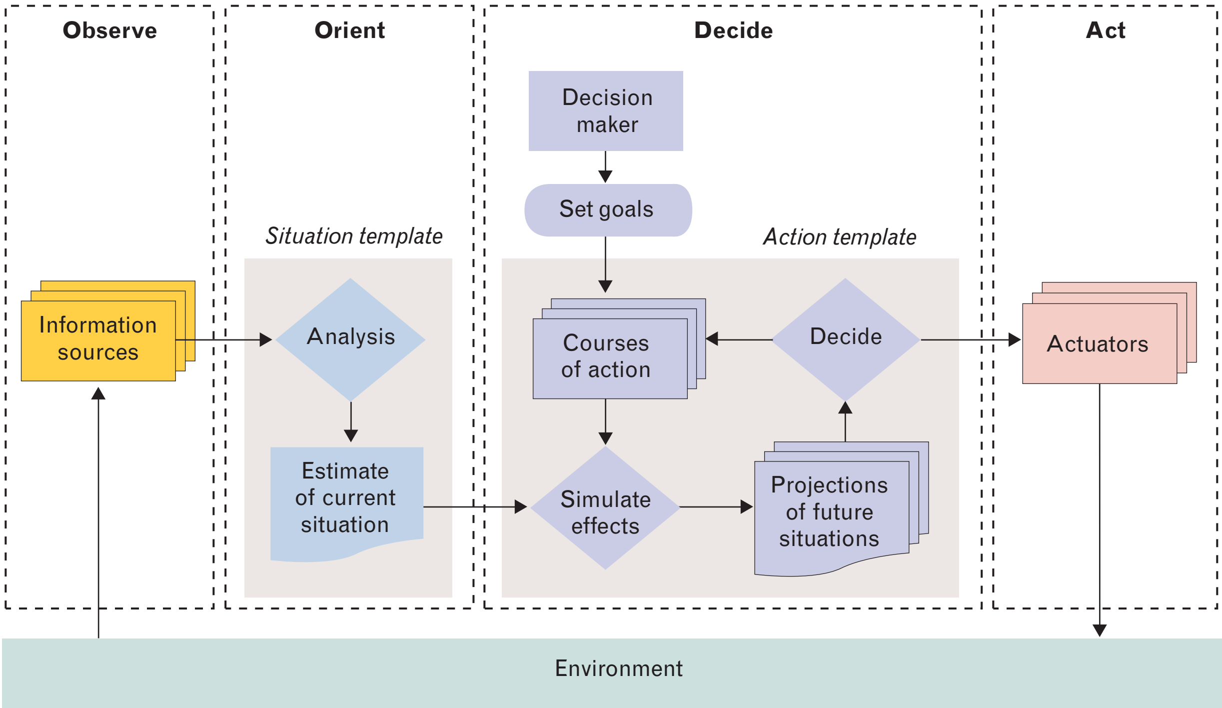

FIGURE 4. The integrated sensing and decision support (ISDS) model combines key elements from the OODA, MDMP, and RPD models. From the OODA loop, the ISDS model explicitly describes the observation and action functions as the interactions of the decision process with the external environment under consideration. From MDMP, the ISDS model decomposes the decision process to indicate the role of simulation, explicit or otherwise, required to select courses of action based on their ability to drive the current perceived situation to a more desirable future state. And from RPD, the ISDS model recognizes the portions of the decision process that can be synopsized by the recognition of appropriate situation or action templates.

tions fabric. One important outcome of this effort was the characterization of the dependence of collaboration in the battle management process on the quality and relevance of the available surveillance information.

Factoring Weather into Air Traffic Control

Mark Weber and colleagues introduce the use of simulations based upon physical models to allow a decision maker to select among several possible courses of action. By combining computer-generated weather models with candidate aircraft routing options, the Lincoln Laboratory team has demonstrated how to extend the time horizon of air route traffic planners by two or more hours in severe weather conditions. By using the extensive data available from the Corridor Integrated Weather System in the eastern half of the United States, the authors have shown how the air traffic management system's decision making can become "weather informed." Special emphasis has been placed upon the development of operator display tools that help the traffic planner visualize directly how various routing options will translate into changes in airspace operations efficiency. Another research thrust discussed in this article is the extent to which domain-specific modeling services can be developed to facilitate interoperability between various decision-making agencies: in this case the development of a service-oriented weather decision support architecture is proposed as an enabler for consolidating weather forecasting systems across the National Airspace System, as well as providing cross-mission services to other agencies, such as the Department of Homeland Security.

Averting Midair Collisions

The article on the Traffic Collision Avoidance System (TCAS) by Jim Kuchar and Ann Drumm illustrates the use of avoidance maneuver templates to provide robust advisories under severe time pressure to resolve airspace conflicts between aircraft. This worldwide-deployed system uses a carefully engineered operator interface to insure comprehensible situation awareness prior to the

generation of resolution advisories. The focus of the current research is on the development of modified action templates to take into consideration previously unanticipated contingencies, such as a pilot reversing the sense of a coordinated resolution maneuver. The authors have extensively analyzed the likelihood of such events by reviewing data recorded by the Lincoln Laboratory monitoring program in the Boston area, and they have developed comprehensive collision risk Monte Carlo simulations to assess the impact of potential changes to the decision logic. The confidence obtained in these results has led the authors to begin investigating the impact of extending TCAS to include conflicts with unmanned aircraft.

Keeping Satellites Apart

The article on space situational awareness by Richard Abbot and Timothy Wallace illustrates the timely identification of potential collision risks among spacecraft in geosynchronous orbits. This task entails automating the generation of situation templates based upon physical models. The most challenging cases involve situations wherein at least one of the spacecraft is not under active control. This case has led the authors to consider Bayesian networks as a solution framework.

Simulating Complex Scenarios

In their article on Virtual Hammer, Paul Metzger and colleagues have demonstrated the use of simulated scene generation and sensor models to extend the applicability of expensive field exercises under controlled variations in the decision support architecture. The authors adopt an approach similar to that used in evaluating ballistic missile defense architectures for the ISR mission. In this case, however, they focus on the demands introduced when multiple operators compete for a small set of sensor resources.

Providing Regional Air Defense

In the final piece on ISDS, Curt Davis, Jim Flavin, and colleagues provide an end-to-end example of a modern decision support environment, in enhanced regional situational awareness. The authors illustrate the integration of all of the elements of distributed sensing, situation analysis, action templates, and decision support for regional air defense under stressing timelines. The architecture also demonstrates the use of effects-based feedback from warning lights and interceptors that help clarify pilot intent when suspicious behavior is observed.

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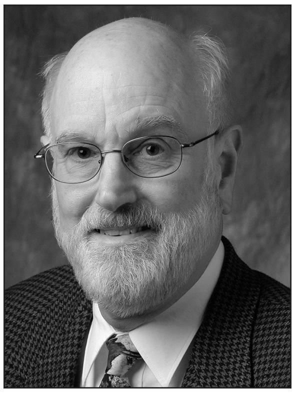

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